Evidence For An Anomalous Like-sign Dimuon Charge Asymmetry

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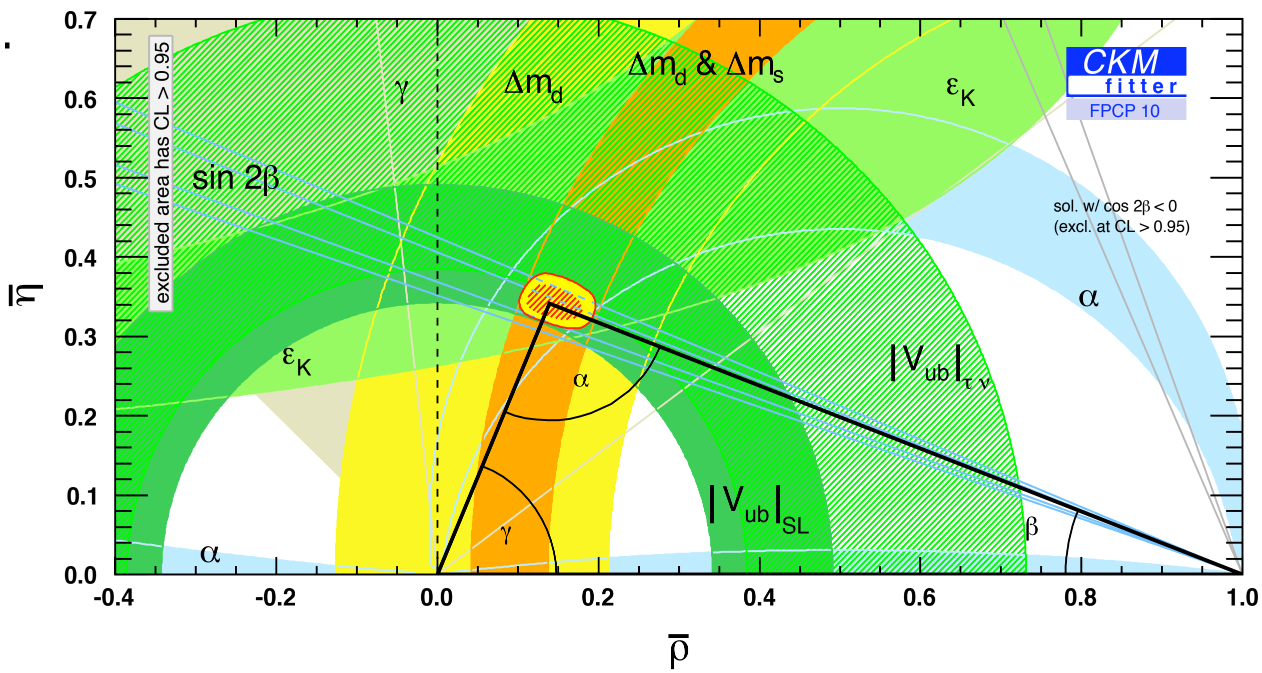
Matter Dominance and CP Violation

The universe we observe today is dominated by matter, **but** we expect matter and antimatter were created in equal amounts at the Big Bang.

At some point a small asymmetry developed. CP violation (CPV) is required to generate such an asymmetry (A. Sakharov).

CPV is naturally included in the standard model (SM) through the quark mixing (CKM) matrix.

Many different measurements of CPV phenomena are in excellent agreement with the SM.



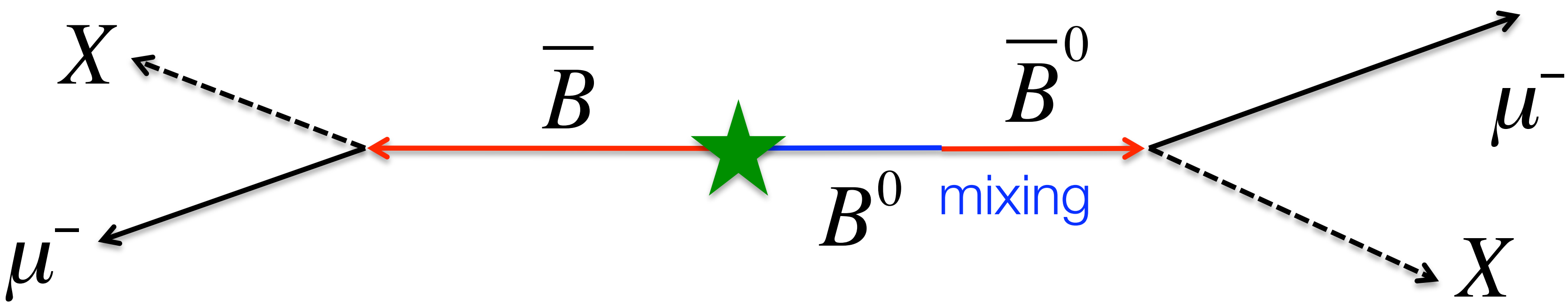
However, the level of CPV predicted by the SM is far **too small** to explain the observed matter dominance.

The search for new sources of CPV is one of the most important tasks in experimental particle physics.

Dimuon Charge Asymmetry

We measure CPV in neutral B meson mixing using the same-sign dimuon charge asymmetry of semileptonic B decays:

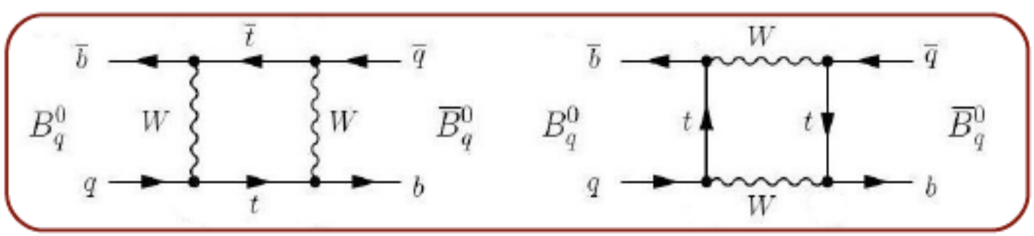
$$\boxed{A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}}$$



One muon comes from direct semileptonic decay: $b \to \mu^- X$

Second muon comes from direct semileptonic decay **after** neutral B meson mixing: $B^0 \to \overline{B}^0 \to \mu^- X$

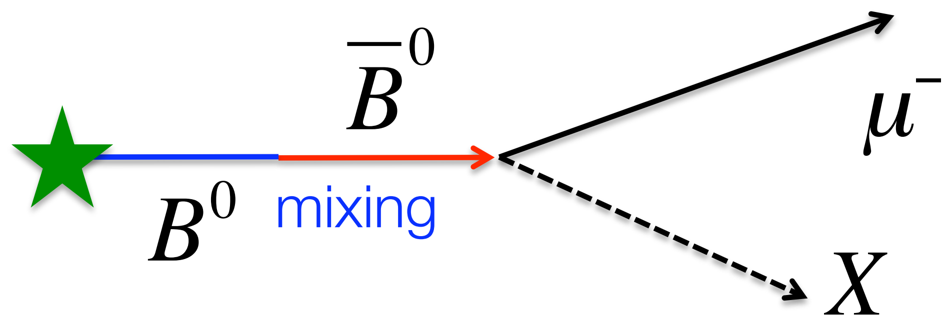
Asymmetry can occur if mixing rates are different: $R\left(B_s^0 \to \overline{B}_s^0\right) \neq R\left(\overline{B}_s^0 \to B_s^0\right)$



Inclusive Muon Charge Asymmetry

Because any dimuon asymmetry arises from the meson mixing, A^b_{sl} is equal to the charge asymmetry a^b_{sl} of "wrong sign" (oscillated) semileptonic decays:

No 'opposite side' muon required: more events, more background processes.



$$\boxed{a^b_{sl} \equiv \frac{\Gamma\left(\overline{B} \to \mu^+ X\right) - \Gamma\left(B \to \mu^- X\right)}{\Gamma\left(\overline{B} \to \mu^+ X\right) + \Gamma\left(B \to \mu^- X\right)} = A^b_{sl}}$$

Grossman, Nir, Raz, PRL 97:151801 (2006)

We have two ways of measuring A^b_{sl}:

Dimuon charge asymmetry	(upper-case symbols)
Inclusive muon charge asymmetry	(lower-case symbols)

A^b_{sl} at the Tevatron

The inclusive muon charge asymmetry can also be defined separately for specific flavors, B_d and B_s, and related to the meson mixing parameters **ΔM, ΔΓ, ϕ_q** (q=d,s)

$$a^q_{sl} \equiv \frac{\Gamma\left(\overline{B}^0_q \to \mu^+ X\right) - \Gamma\left(B^0_q \to \mu^- X\right)}{\Gamma\left(\overline{B}^0_q \to \mu^+ X\right) + \Gamma\left(B^0_q \to \mu^- X\right)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

Both B_d and B_s are produced at the Tevatron, so both contribute to A^b_{sl}

$$A^b_{sl} = (0.506 \pm 0.043) a^d_{sl} + (0.494 \pm 0.043) a^s_{sl}$$

SM prediction is negligible compared to current experimental precision:

$$A^b_{sl}(SM) = \left(-2.3^{+0.5}_{-0.6}\right) \times 10^{-4}$$

Using prediction of a_{sl}^d and a_{sl}^s from A. Lenz, U. Nierste, hep-ph/0612167

A measurement of CPV significantly different from zero would be clear evidence of new physics

DØ Detector

DØ records $p\bar{p}$ interactions at 1.96 TeV: matter-antimatter symmetric

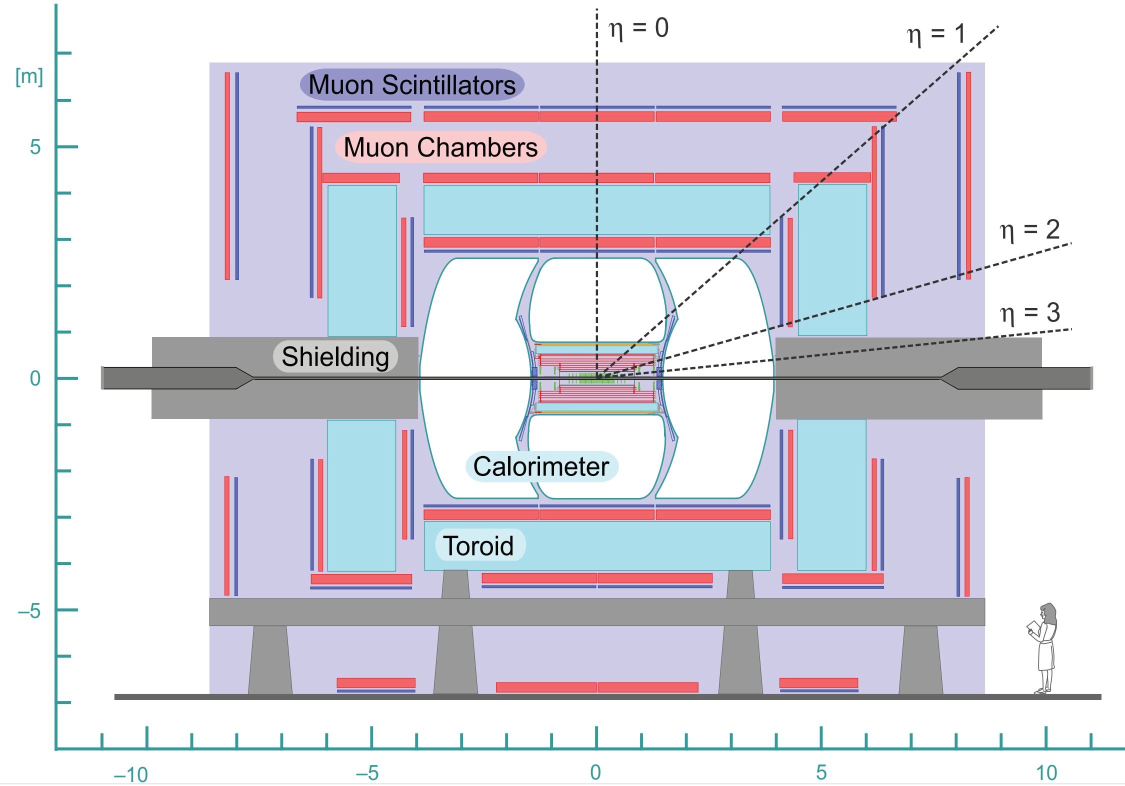
Two magnets:

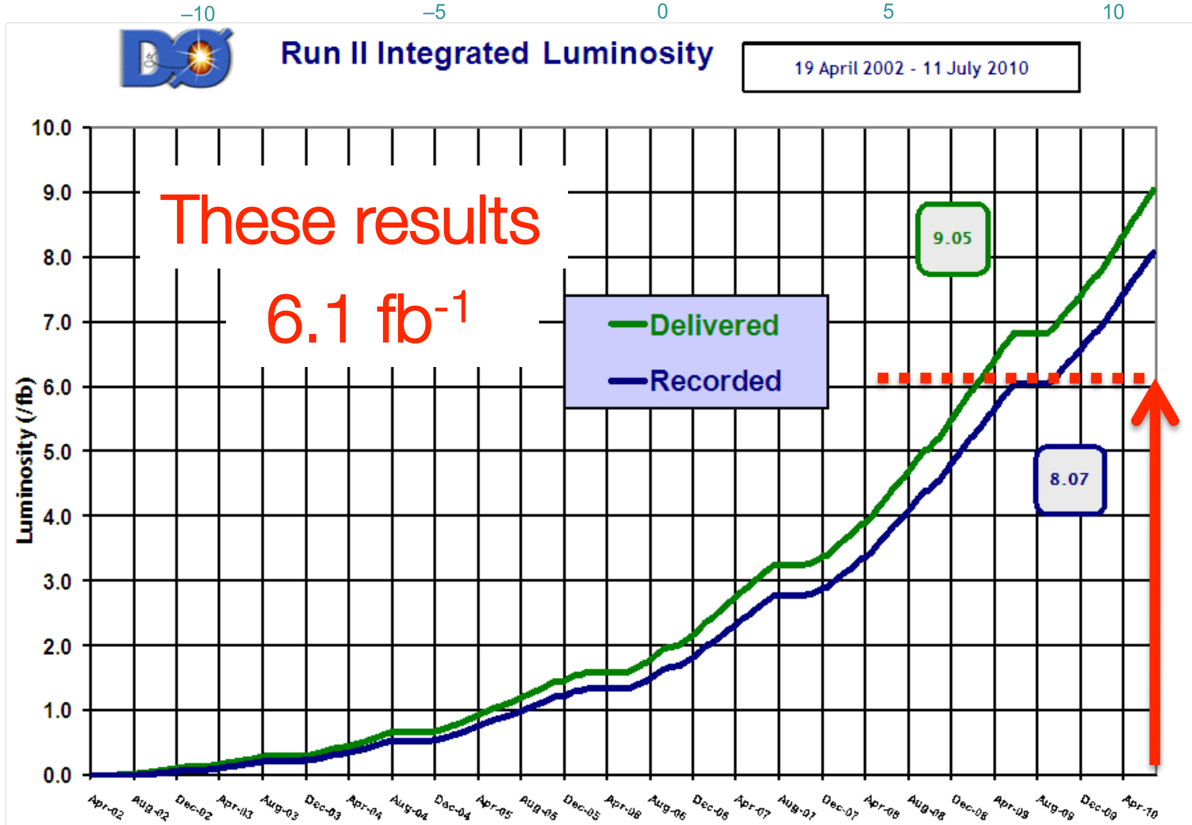
2T central solenoid

1.8T muon toroid

Bi-weekly polarity changes ensures nearly equal datasets with each configuration: ++, +−, −+, −−.

Regular magnet flipping significantly reduces systematics in charge asymmetry measurements.





Raw Asymmetries

Experimentally we measure two quantities (by counting events):

Inclusive muon charge asymmetry

$$\boxed{a \equiv \frac{n^+ - n^-}{n^+ + n^-}}$$

Like-sign dimuon charge asymmetry

$$\boxed{A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}}$$

Event selection:

Track-matched muon, $|\eta| < 2.2$;
$1.5 < p_T < 25$ GeV;

$p_T > 4.2$ GeV, or $|p_z| > 6.4$ GeV;

Distance to primary vertex < 3 mm in axial plane, < 5 mm along the beam.

Both muons must pass inclusive muon selection;

Like sign, same primary vertex;

$M(\mu\mu) > 2.8$ GeV to suppress events with two muons from the same B decay.

$$\boxed{a = (+0.955 \pm 0.003)\%}$$

(from 1.5×10^9 single muon events)

$$\boxed{A = (+0.564 \pm 0.053)\%}$$

(from 3.7×10^6 like-sign dimuon events)

Extracting A^b_{sl}

Both A and a linearly depend on the charge asymmetry A^b_{sl}

$$\boxed{\begin{aligned} a &= k\,A^b_{sl} + a_{bkg} \\ A &= K\,A^b_{sl} + A_{bkg} \end{aligned}}$$

recalling $A^b_{sl} = a^b_{sl}$

A_{bkg} and a_{bkg} are the detector related background contributions to the measured asymmetry;

Coefficients K and k are small (< 1) due to the effect of charge symmetric background processes which dilute the semileptonic asymmetry.

Strategy:

1) Determine the background contributions A_{bkg} and a_{bkg};
2) Find the coefficients K and k;
3) Extract the asymmetry A^b_{sl}.

Final result was blinded until all analysis methods were fixed.

Background Contribution a_{bkg}, A_{bkg}

$$a = k\,A_{sl}^{b} + a_{bkg}$$

$$A = K\,A_{sl}^{b} + A_{bkg}$$

These terms account for effects from:

- Decays $K^{\pm} \to \mu^{\pm}\nu, \pi^{\pm} \to \mu^{\pm}\nu$;
- Hadronic punch-through to the muon detector;
- Muon reconstruction asymmetries;
- Asymmetries in tracks wrongly associated with muons.

All background contributions are measured directly in the data, with reduced input from simulation.

e.g. for inclusive muon asymmtry:

$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{bkg}\right)\delta$$

kaon pion proton

fraction asymmetry

Muon reconstruction asymmetry

Example: Asymmetry from Kaons

$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{bkg}\right)\delta$$

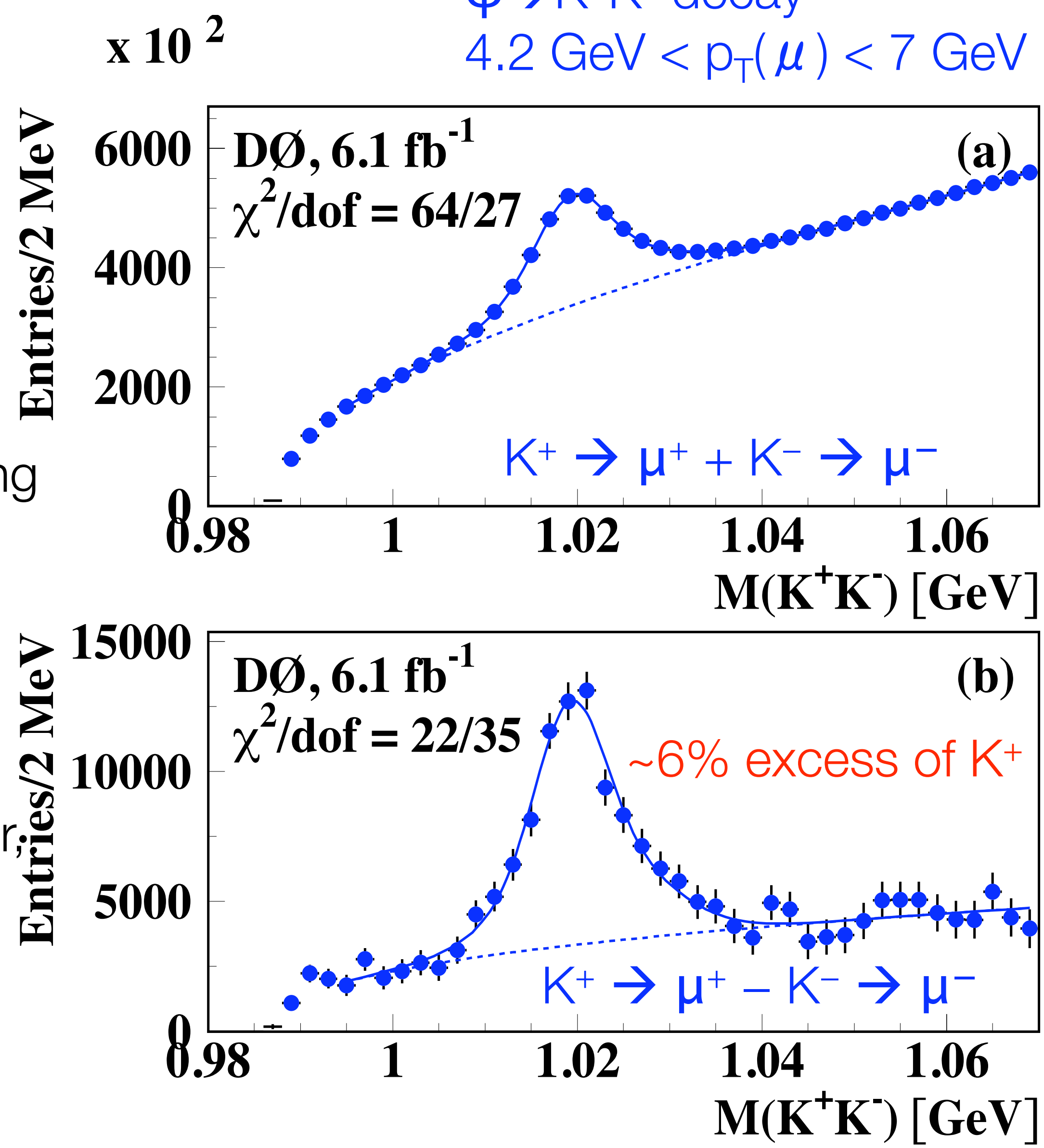
To determine a_{bkg} and A_{bkg} we must know the 7 parameters $a_{K,\pi,p}$, $f_{K,\pi,p}$, δ and the corresponding dimuon parameters.

Example: Kaon asymmetry measured using decays $K^{*0} \rightarrow K^+\pi^-$ and $\phi(1020) \rightarrow K^+K^-$ by fitting mass peaks to find asymmetry.

Asymmetry is positive since K^+ are less likely to interact with matter in the detector, so they have better chance to decay to muons before interaction.

$\phi \rightarrow K^+K^-$ decay

4.2 GeV < $p_T(\mu)$ < 7 GeV



Summary of Background Contributions

Inclusive
$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{bkg}\right)\delta$$

Like-sign dimuon
$$A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(2 - F_{bkg}\right)\Delta$$

	$f_K a_K$ or $F_K A_K$ (%)	$f_\pi a_\pi$ or $F_\pi A_\pi$(%)	$f_p a_p$ or $F_p A_p$(%)	$(1\text{-}f_{bkg})\delta$(%) or $(2\text{-}F_{bkg})\Delta$(%)	a_{bkg} or A_{bkg}
Inclusive	0.854±0.018	0.095±0.027	0.012±0.022	-0.044±0.016	0.917±0.045
Dimuon	0.828±0.035	0.095±0.025	0.000±0.021	-0.108±0.037	0.815±0.070

All uncertainties are statistical only;

Dominant effect comes from kaons, as expected;

Background contribution is similar for inclusive muon and dimuon samples: $A_{bkg} \approx a_{bkg}$

Dilution

After subtracting the background contribution from the "raw" asymmetries a and A, the remaining residual asymmetry is proportional to A^b_{sl}

$$\boxed{\begin{aligned} k\,A^b_{sl} &= a - a_{bkg} \\ K\,A^b_{sl} &= A - A_{bkg} \end{aligned}}$$

Coefficients k and K take into account the dilution of the raw asymmetries a and A from decays of other heavy quarks to muons

k and K are determined using a simulation of b and c-quark decays

$$\boxed{\begin{aligned} &k = 0.041 \pm 0.003 \\ &K = 0.342 \pm 0.023 \quad k/K = 0.12 \pm 0.01 \end{aligned}}$$

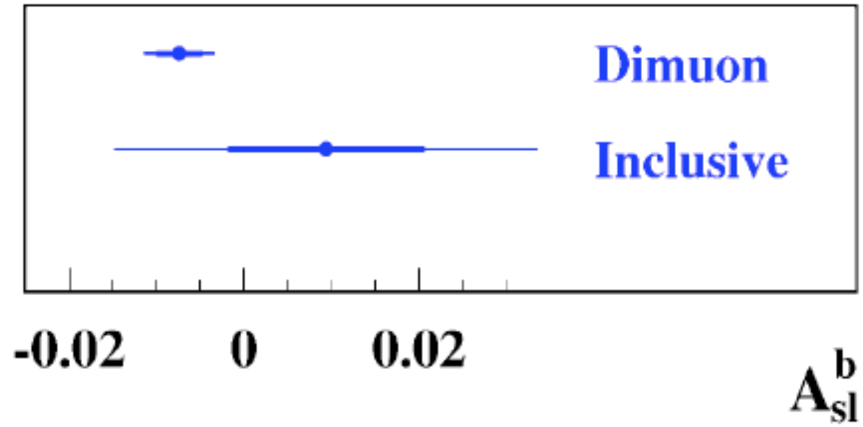
k is found to be much smaller than K because many more non-oscillating b and c-quark decays contribute to the inclusive muon asymmetry

Results: Part I

A^b_{sl} is extracted separately from both the inclusive muon (a) and like-sign dimuon (A) methods:

From a: $A^b_{sl} = \left(+0.94 \pm 1.12\,(stat) \pm 2.14\,(syst)\right)\%$

From A: $A^b_{sl} = \left(-0.736 \pm 0.266\,(stat) \pm 0.305\,(syst)\right)\%$



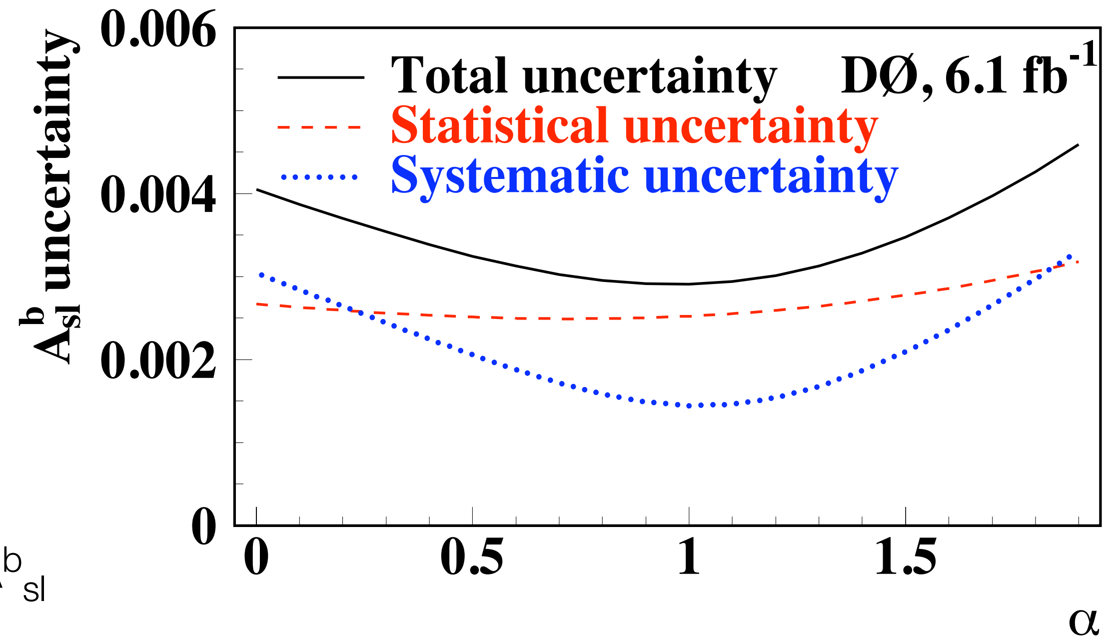
The background a_{bkg} and A_{bkg} are strongly correlated (same sources contribute to both), so we can construct a linear combination such that the total uncertainties are minimized.

$$\boxed{A' \equiv A - \alpha a = (K - \alpha k) A^b_{sl} + \left(A_{bkg} - \alpha a_{bkg}\right)}$$

We can expect minimum uncertainties for $\alpha \approx 1$, since background asymmetries are similar. We retain sensitivity to A^b_{sl} since K >> k.

Results: Part II

Scan over total uncertainty on final measurement yields **α=0.959**



Reduces overall systematic uncertainty

Precision is now **statistically limited**

From A' = A – αa we obtain a value of A^b_{sl}

$$\boxed{A_{sl}^{b} = \left(-0.957 \pm 0.251\,(stat) \pm 0.146\,(syst)\right)\%}$$

This result differs from the SM prediction by 3.2 **σ**

$$\boxed{A_{sl}^{b}(SM) = \left(-2.3^{+0.5}_{-0.6}\right) \times 10^{-4}}$$

The measured asymmetry **favors the production of matter over antimatter** in semileptonic decays of oscillated neutral B mesons.

Uncertainties

Source	A^b_{sl} *Inclusive* $\sigma(A^b_{\rm sl})(59)$	A^b_{sl} *Dimuon* $\sigma(A^b_{\rm sl})(60)$	A^b_{sl} *Combined* $\sigma(A^b_{\rm sl})(62)$
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

Dominant uncertainties

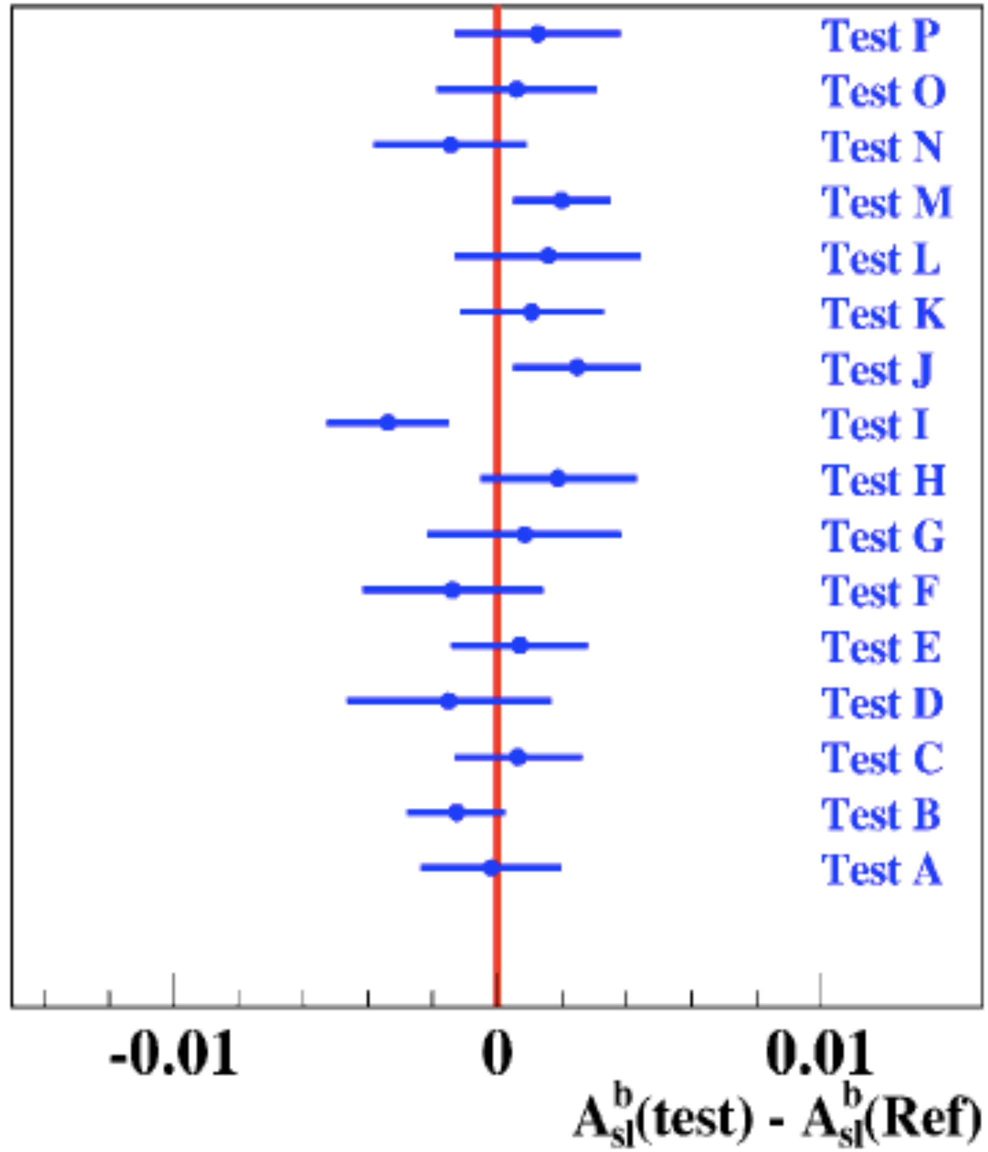
Consistency Tests

We modify the selection criteria, or use a sub-set of data, to test the stability of the final result:

16 tests in total are performed;

There is significant variation of the raw asymmetries a and A (up to 140%) due to changes in the background composition;

However, A^b_{sl} remains stable in all tests.



The developed method is stable and gives a consistent result after modifying selection criteria over a wide range.

Comparison With Other Measurements

In this analysis we measure a linear combination of a^d_{sl} and a^s_{sl}

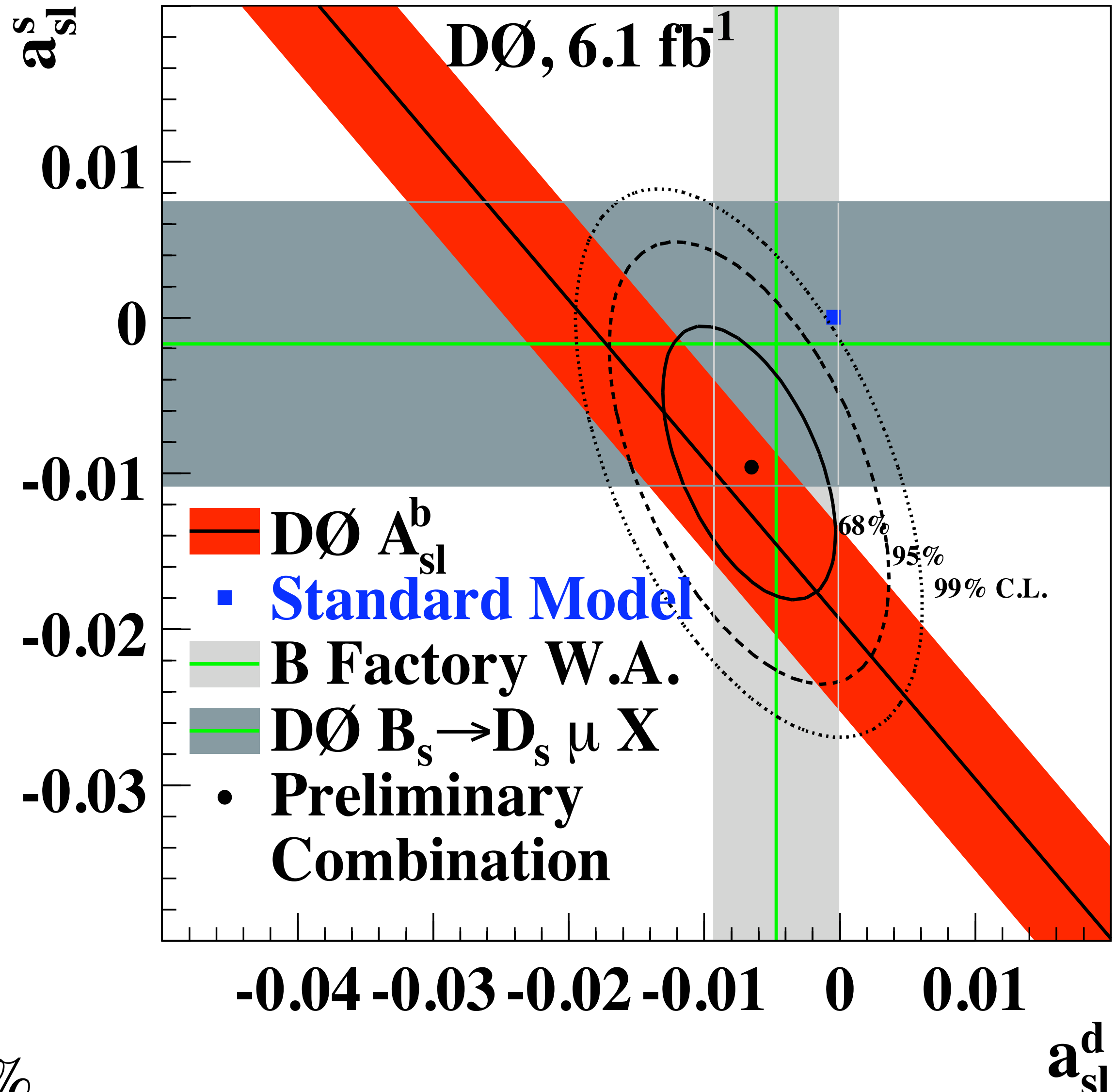
$$A^b_{sl} = 0.506\, a^d_{sl} + 0.494\, a^s_{sl}$$

Result agrees well with other measurements of a^d_{sl} and a^s_{sl}

The value of a^s_{sl} can also be extracted using additional input from a^d_{sl} from B factories:

$$\boxed{a^s_{sl} = (-1.46 \pm 0.75)\%}$$

$$a^b_{sl}(SM) = (+0.0021 \pm 0.0006)\%$$



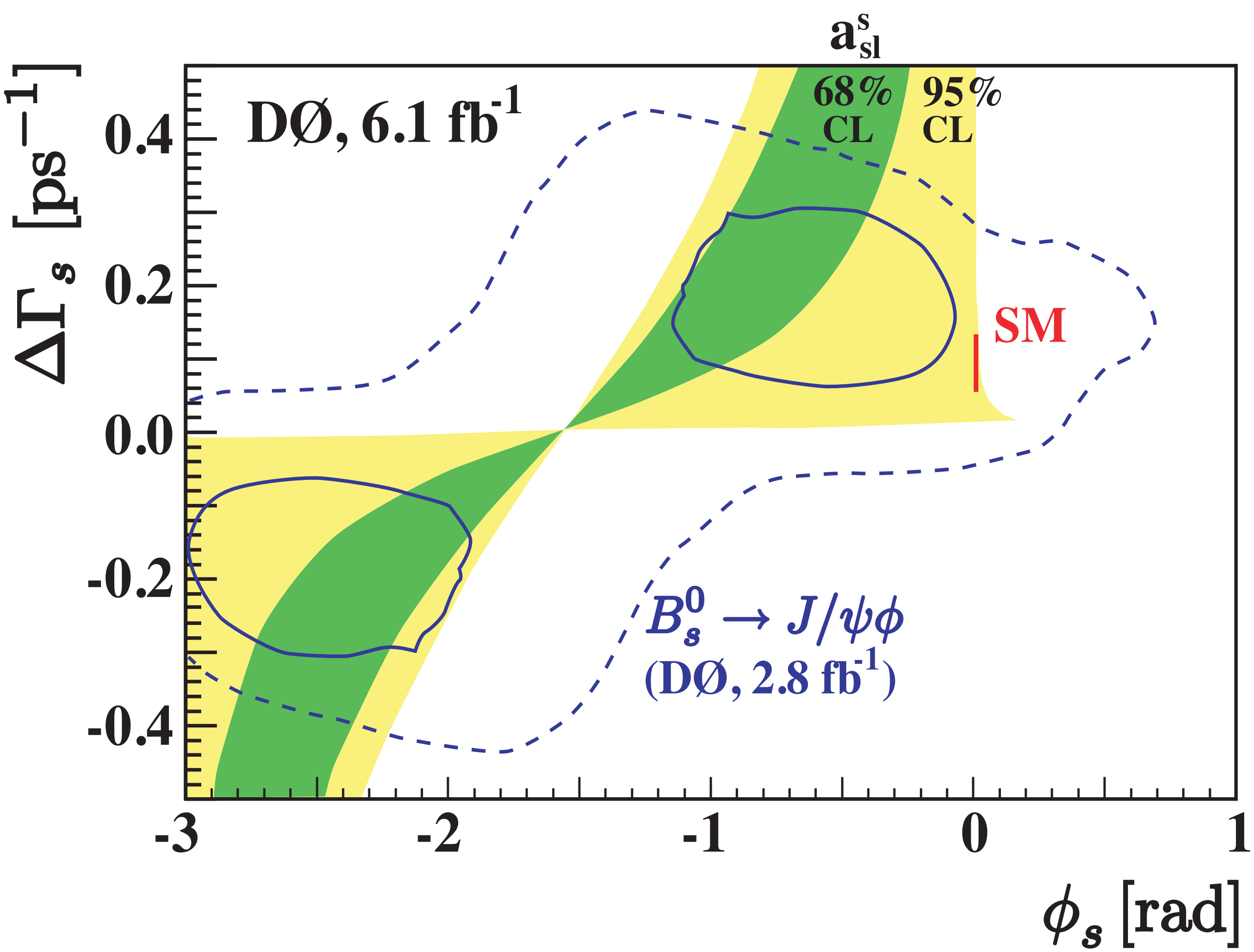
arXiv:1005.2757 [hep-ex]

PRD accepted. PRL in progress.

Constraining B_s^0 Mixing Parameters

The value a^s_{sl} can be further translated into a 2D constraint on the CPV phase ϕ_s and width difference $\Delta\Gamma_s$.

The contours are in excellent agreement with independent measurements of ϕ_s and $\Delta\Gamma_s$ in $B_s^0 \to J/\psi\phi$ decays from DØ and CDF.



$$a_{sl}^q = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q$$

Conclusions

We provide evidence of an anomalous charge asymmetry in the number of muons produced in the initially CP symmetric $p\bar{p}$ interaction.

$$\boxed{A_{sl}^{b} = \left(-0.957 \pm 0.251\,(stat) \pm 0.146\,(syst)\right)\%}$$

This asymmetry disagrees with the SM prediction at the level of 3.2σ.

This measurement was obtained using very little input from simulation, and all tests show excellent consistency.

This new result is consistent with other measurements.

We observe that the number of produced particles of matter (μ^-) is larger than the number of produced particles of antimatter.

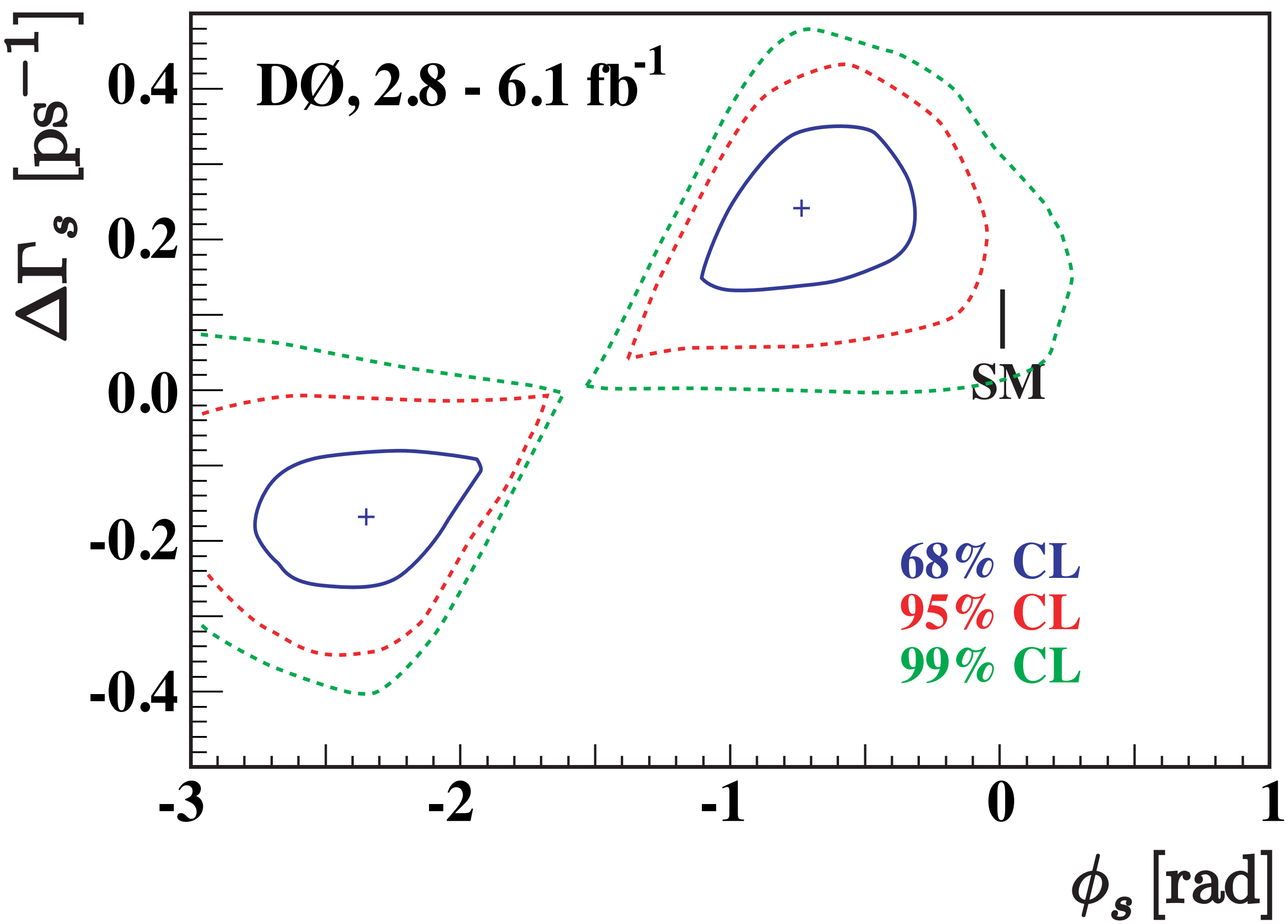
The sign of observed asymmetry is consistent with the sign of CP violation required to explain the observed abundance of matter in the Universe.

Backup Material

Combination of Results

The measurement and the result of the DØ analysis in $B_s^0 \rightarrow J/\psi\phi$ can be combined

This combination excludes the SM value of ϕs at more than 95% C.L.

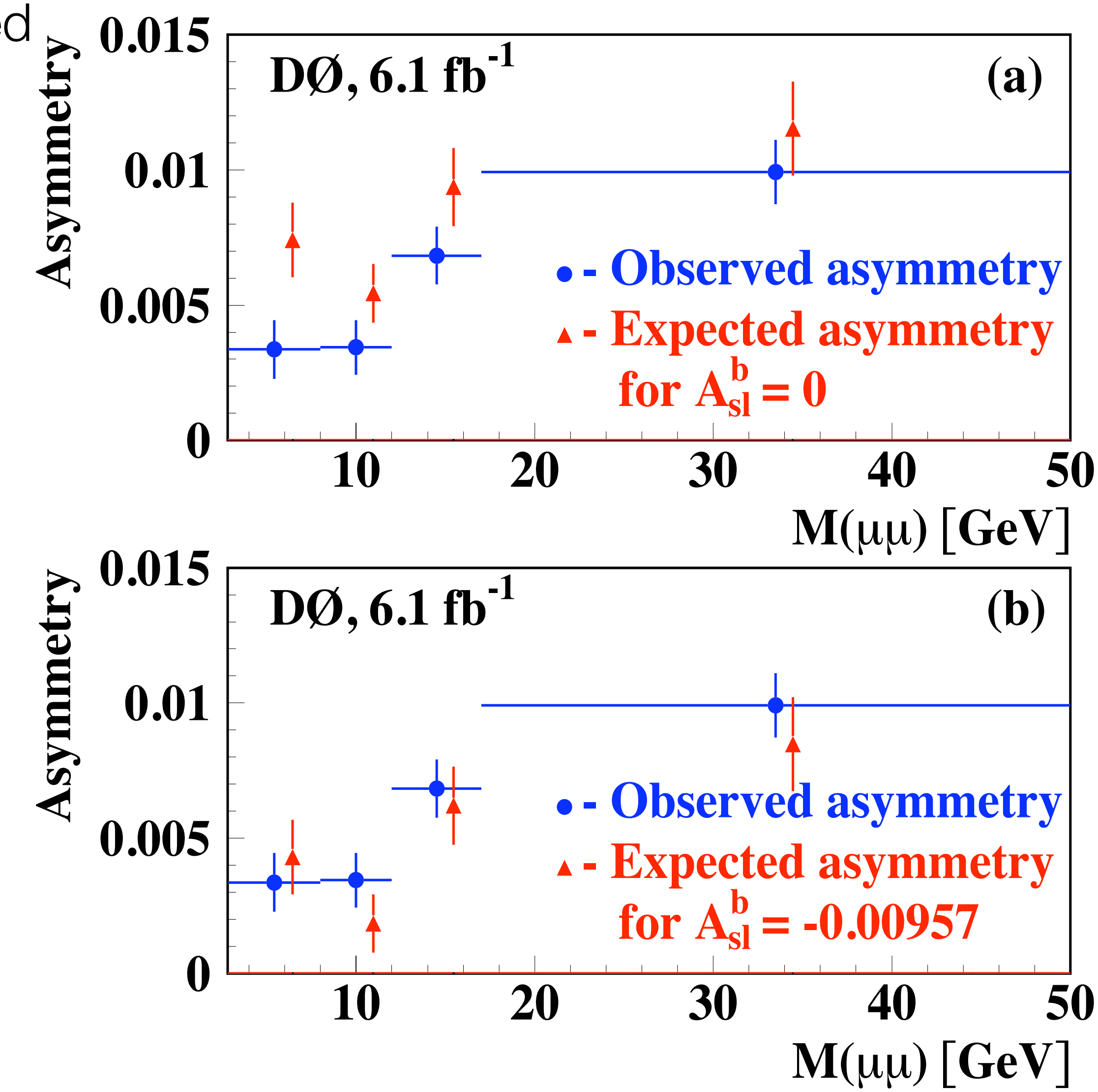


Dependence on Dimuon Mass

We compare the expected and observed raw dimuon charge asymmetry A for different invariant masses M(μμ)

The expected and observed asymmetries agree well for $A^b_{sl} = -0.00957$

Agreement is over the entire M(μμ) range, and supports B physics as the source of anomalous asymmetry



Dependence on the dimuon mass is well described by the analysis method.

Tests A – C

A: Using only the part of the data sample corresponding to the first 2.8 fb^{-1}.

B: In addition to the reference selection, require at least three hits in muon wire chamber layers B or C, and the χ^2 for a fit to a track segment reconstructed in the muon detector to be less than 8.

C: Since the background muons are produced by decays of kaons and pions, their track parameters measured by the central tracker and by the muon system are different. therefore, the fraction of background strongly depends on the χ^2 of the difference between these two measurements. The requirement on this χ^2 is changed from 40 to 4 in this study.

Tests D – F

D: The requirement on the transverse impact parameter is changed from 0.3 to 0.05 cm, and the requirement on the longitudinal distance between the point of closest approach to the beam and the associated primary vertex is changed from 0.5 to 0.05 cm (this test serves also as a cross-check against the possible contamination from muons from cosmic rays in the selected sample.

E: Using only low-luminosity events with fewer than three primary vertices.

F: Using only events with the same polarities of the solenoidal and toroidal magnets.

Tests G – J

G: Changing the requirement of the invariant mass of the two muons from 2.8 GeV to 12 GeV.

H: Using the same muon pT requirement, pT > 4.2 GeV, over the full detector acceptance.

I: Requiring the muon pT to be pT < 7.0 GeV.

J: Requiring the azimuthal angle ϕ of the muon track to be in the range $0 < \phi < 4$ or $5.7 < \phi < 2\pi$. This selection excludes muons directed to the region of poor muon identification efficiency in the support structure of the detector.

Tests K – N

K: Requiring the muon η be in the range $|\eta| < 1.6$ (this test serves also as a cross-check against the possible contamination from muons associated with the beam halo.

L: Requiring the muon η be in the range $|\eta| < 1.2$ or 1.6 $|\eta|$ 2.2.

M: Requiring the muon η be in the range $|\eta| < 0.7$ or $1.2 < |\eta| < 2.2$.

N: Requiring the muon η be in the range $0.7 < |\eta| < 2.2$.

Background Contributions

$$a = k\,A_{sl}^{b} + a_{bkg}$$

$$A = K\,A_{sl}^{b} + A_{bkg}$$

$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{bkg}\right)\delta$$ Inclusive muon sample

$$A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(2 - F_{bkg}\right)\Delta$$ Dimuon sample

f_K, f_π, f_p, F_K, F_π, F_p are the fractions of kaons, pions and protons identified as a muon in the single and dimuon samples;

a_K, a_π, a_p, A_K, A_π, A_p are the charge asymmetries of kaon, pion, and proton tracks;

δ and Δ are the charge asymmetry of muon reconstruction

$f_{bkg} = f_K + f_\pi + f_p$, and $F_{bkg} = F_K + F_\pi + F_p$

Background Contributions

$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{bkg}\right)\delta$$

$$A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(2 - F_{bkg}\right)\Delta$$

Final piece of the equation needed to determine a_{bkg} and A_{bkg}

Reversal of toroid and solenoid polarities cancels 1st – order detector effects;

Quadratic terms in detector asymmetries still can contribute into the muon reconstruction asymmetry;

Detector asymmetries for a given magnet polarity adet ≈ O(1%);

We can expect the residual reconstruction asymmetry:

$$\delta \approx \Delta \approx O(0.1\%)$$

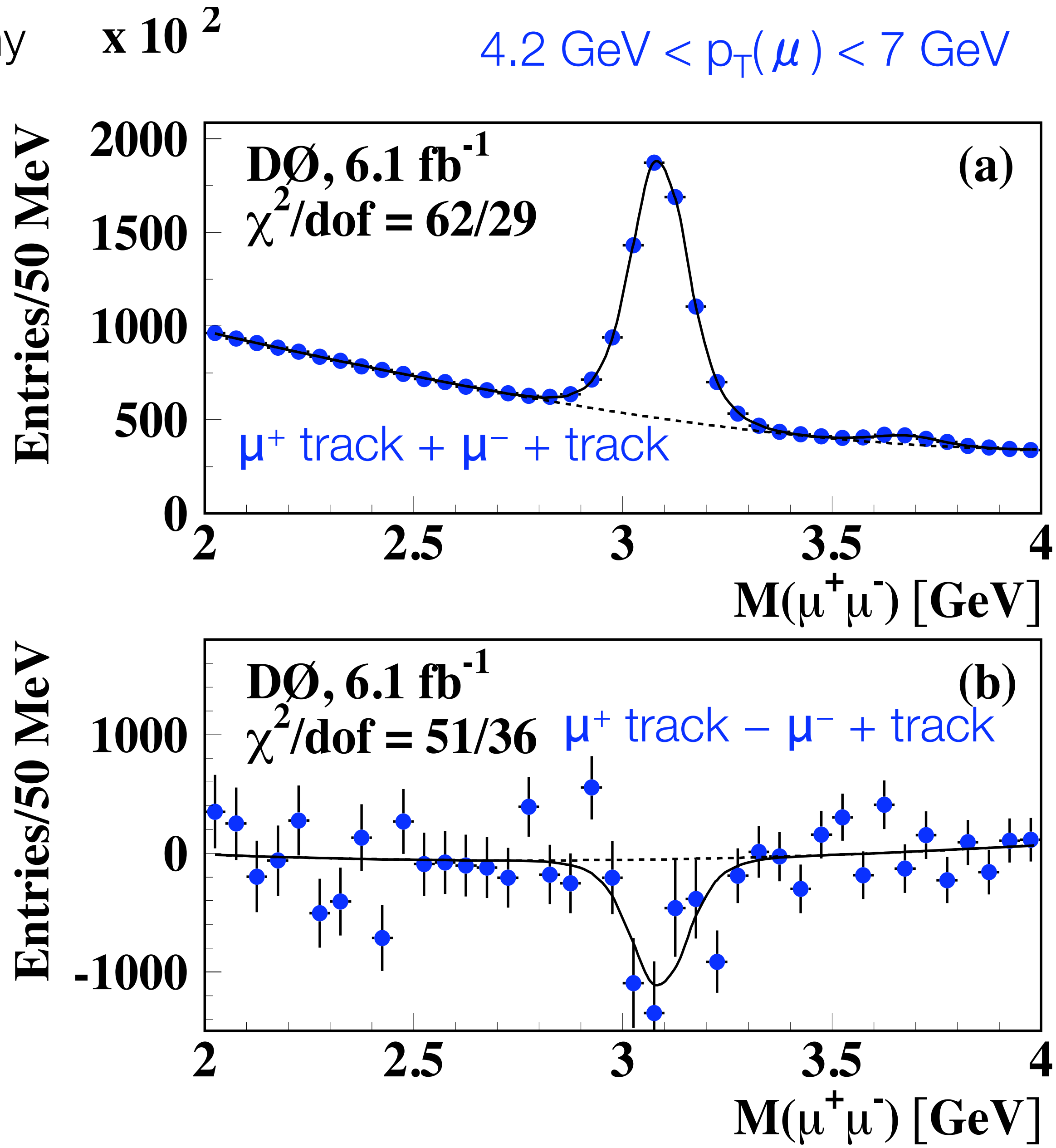
Muon Reconstruction Asymmetry

We measure the muon reconstruction asymmetry using $J/\psi \rightarrow \mu\mu$ events, where a muon is combined with any track of opposite charge.

$\delta = (-0.076 \pm 0.028)\%$

$\Delta = (-0.068 \pm 0.023)\%$

Direct benefit of regular magnet polarity reversal!



Kaons Detection Asymmetry

$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{bkg}\right)\delta$$

$$A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(2 - F_{bkg}\right)\Delta$$

The largest background asymmetry comes from the charge asymmetry of kaon tracks Identified as a muon;

The interaction cross-section of K^+ and K^- with the detector material is different, especially for kaons with low momentum;

The reaction $K^-N \rightarrow Y\pi$ has no K^+N analog;

K^+ travels further than K^- in detector material on average and has a better chance of decaying to a muon, or punching-through the muon system

a_K, A_K should be a positive asymmetry

Other asymmetries are ~10× smaller

Pion and Proton Background Asymmetries

$$a_{bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{bkg}\right)\delta$$

$$A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(2 - F_{bkg}\right)\Delta$$

The same strategy is used to determine a_π, a_p, A_π and A_p.

$K_S \rightarrow \pi^+\pi^-$ is used to measure pion asymmetry

$\Lambda \rightarrow p\pi^-$ is used to measure proton asymmetry

	a_K(%)	a_π(%)	a_p(%)
Data	5.51±0.11 Largest contribution	0.25±0.10	2.3±2.8 Low statistics

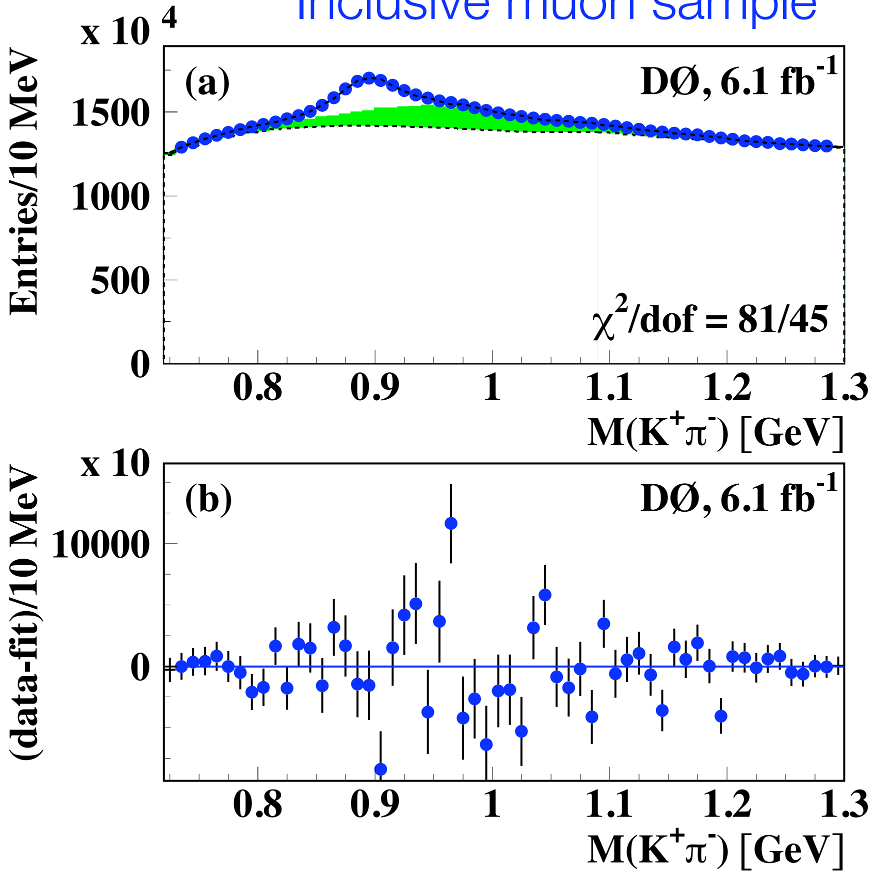
Measurement of f_K and F_K

Fractions f_K and F_K are measured using the decays $K^{*0} \rightarrow K^+\pi^-$ selected in the inclusive muon and like-sign dimuon samples, respectively.

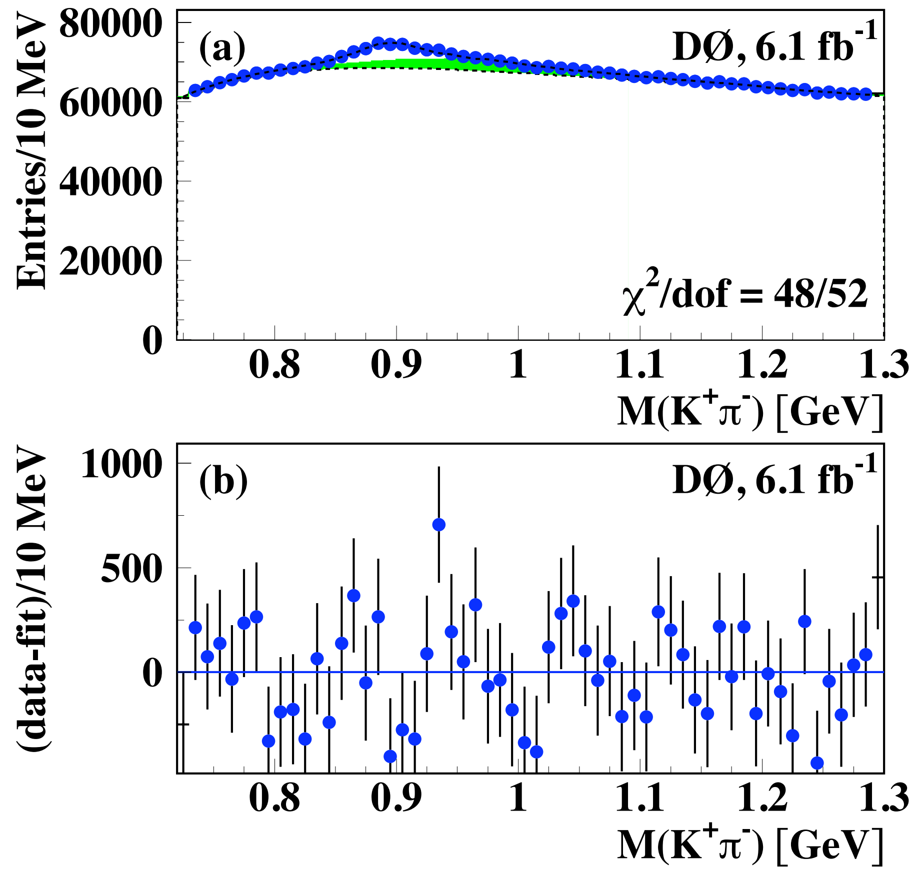
Kaon is required to be identified as a muon.

We measure fractions f_K^{*0} and F_K^{*0}.

Inclusive muon sample



Like-sign dimuon sample



Reducing the Uncertainty

Single muon asymmetry completely dominated by background, and background systematic is dominant

Use a to constrain background asymmetry uncertainty in dimuons

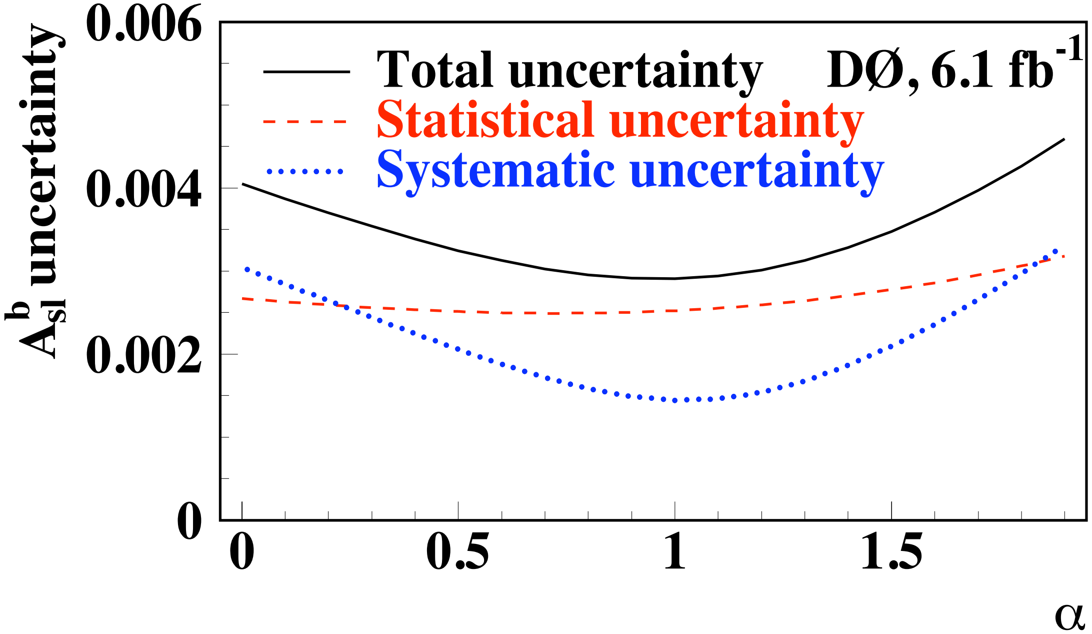
$$A' = (A - \alpha a) = (K - \alpha k) A_{sl}^{b} + (A_{bkg} - \alpha a_{bkg})$$

Choose **α** to minimize uncertainty on A_{sl}^{b}

α will be close to 1 since the backgrounds are highly correlated

$$A_{bkg} = (+0.815 \pm 0.070)\%$$

$$a_{bkg} = (+0.917 \pm 0.045)\%$$



Magnetic Polarity Reversal

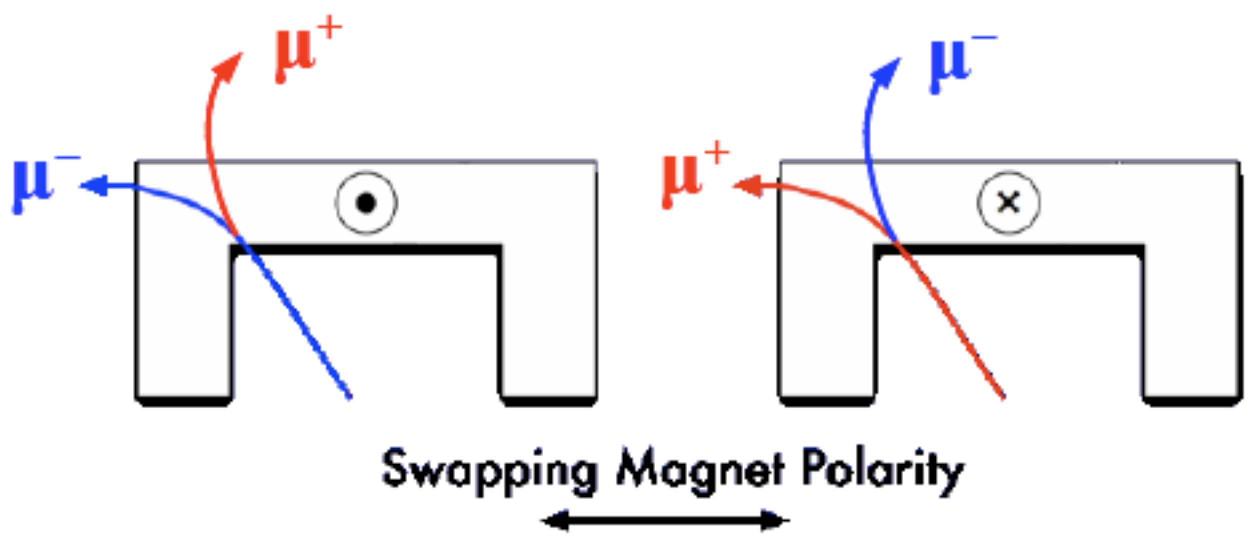
Polarities of solenoid and toroid are reversed regularly

Trajectory of the negative particle becomes exactly the same as the trajectory of the positive particle with the reversed magnetic polarity

4 samples analyzed with different polarities (++, −−, +−, −+)

The difference in the reconstruction efficiency between positive and negative particles is minimized

Changing polarities is an important feature of the DØ detector, which reduces significantly systematic uncertainties in charge asymmetry measurements



Kaon Contribution

Can measure f_{K^*}, F_{K^*}

Extract f_K, F_K from

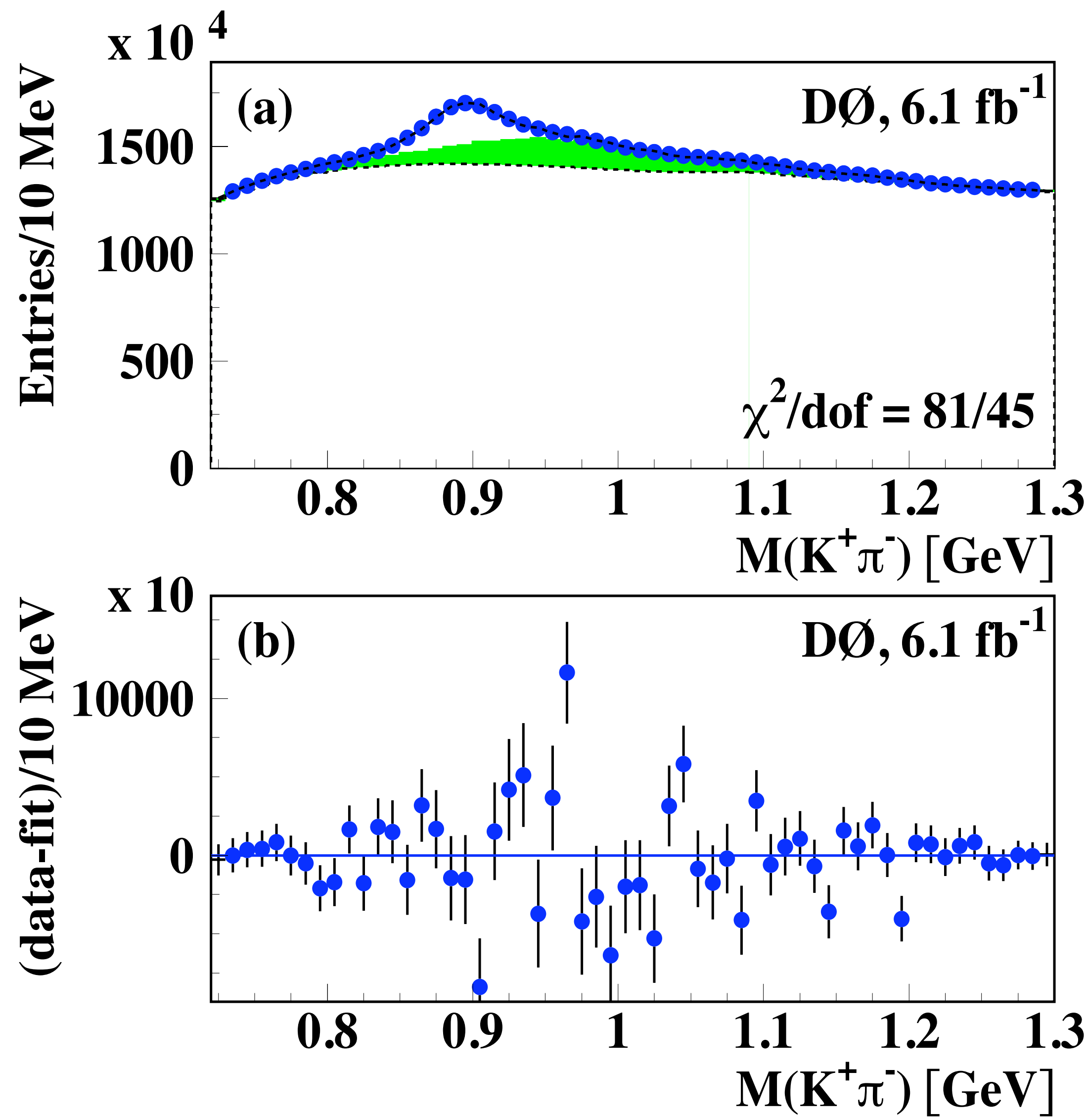
$$f_K = \frac{N(K_S)}{N(K^{*+} \to K_S \pi^+)} f_{K^*}$$

$$F_K = \frac{N(K_S)}{N(K^{*+} \to K_S \pi^+)} F_{K^*}$$

$$= f_K \Big/ f_{K^*}$$

Use simulation to confirm pion reconstruction ε is the same for K^{*+} and K^{*0} if K^+/K_s is reconstructed

Single muon sample



Dominant systematic!

Other Background Contributions

Use n_π/n_K and n_p/n_K from simulation to derive f_π, f_p, F_π and F_p from f_K and F_K (with a check on n_K in data to evaluate uncertainties)

Also adjust for the probabilities for a π, p, K to be reconstructed as a muon (from ϕ, K_s, Λ decays)